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HEAT TRANSFER TO HYDROGEN FLOWING IN A CURVED TUBE

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ABSTRACT

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The effects of curvature, symmetrical heating, on the heat-transfer behavior of subcritical (two-phase), supercritical, and gaseous hydrogen were investigated in four tube geometries. The uniformly heated tube data indicated a substantial difference (up to 3 to 1) between the heat-transfer coefficient on the concave surface (outside of curve as seen by the fluid) and the heat-transfer coefficient on the convex surface (inside of curve). The coefficient on the convex surface while reduced, generally followed the straight tube data at comparable conditions. The magnitude and duration of these effects were found to be a function of the radius of curvature, the angular position, and the proximity of the fluid to the saturation or transposed-critical temperature as it entered the curve. Visual studies of two-phase and single-phase fluids supported the curvature effects. Secondary flow was greatly diminished in the two-phase nitrogen visual tests.

These effects apparently corroborate portions of existing heat-transfer models for hydrogen and provide further insight into the stability and control of the heat-transfer mechanism. AUTHOR

INTRODUCTION

The advent of high performance chemical and nuclear rocket engines has required the designer to predict the local heat-transfer process throughout the cooling system with greater accuracy than previously used approximate methods. The majority of the heat-transfer data taken thus far is applicable only to symmetrically heated, constant cross section, straight tubes. Little consideration has been given to geometric variations such as exist in the cooling passages of a rocket engine. This paper presents salient observations of a program of heat-transfer measurements with curved tubes completed at Lewis Research Center, to be reported more fully in the future.

The range of conditions covered in the experiments and some geometric variations of the test section are tabulated as follows:

Pressure, psia	100, 150, 300, 600
Inlet bulk temperature, $^{\circ}R$	56 to 110
Weight flow, lb_{mass}/sec	0.09 to 0.2
Heat flux, Btu/(sq in.)(sec)	1 to 3.5
Bend angle, deg	26 to 75
Radii of curvature, in.	$7\frac{1}{2}$, $5\frac{1}{2}$, $4\frac{3}{8}$, 2
Nominal tube diameter, in.	1/2, 3/8, 5/16

Apparatus and Instrumentation

The system consists of a high pressure gas forcing liquid hydrogen through metering equipment, the test section, a heat exchanger, and finally exhausting the fluid to the atmosphere (see fig. 1). The test section consisted of an electrically heated curved tube with skewed bus connections instrumented with thermocouples, pressure taps and, voltage taps (see fig. 1).

The Chromel-Alumel thermocouples were formed, cemented, and clamped to the concave and convex surfaces of the test section. The thin layer of cement gave adequate electrical insulation with a minimal thermal insulation.

This technique is unsatisfactory for determining surface temperatures below 200° to 250° R, where the thermocouple output is small and the thermocouple joint tends to loosen.

The entire section was enclosed in a vacuum tank. Flow measurements were determined by a venturi within the liquid hydrogen tank and an orifice located downstream of the heat exchanger. Inlet and outlet pressures and temperatures were measured by using carbon and platinum resistance thermometers or thermocouples in the case of a gas. The power measurements, volts and amperes, were read manually. All other measurements were recorded by an automatic digital potentiometer.

SUMMARY OF OBSERVATIONS

From a series of tests with two-phase, near-critical, gaseous hydrogen, the following observations concerning convective heat transfer on the concave and convex surfaces of curved tubes (fig. 1) of various diameters and curvatures were made:

1. The concave surface enhances and the convex surface degrades the heat transfer. In the experiments, the ratio of the concave to convex heat-transfer coefficients exceeded 3 for near-critical hydrogen and reached 2 for gaseous hydrogen. The magnitude of this ratio depends on the fluid structure, the radius of curvature, the angular position, and the tube diameter.

2. In the near-critical region, the relation between the Eckert parameter (ref. 1), $h_{concave}/h_{convex}$, and the angular position (fig. 2) indicates that a minimum occurs near the transposed critical temperature for the $\frac{1}{2}$-inch-diameter, $5\frac{1}{2}$-inch radius-of-curvature test section (fig. 2). The concave and convex heat-transfer coefficients tend to maximize in this region with the greater increase at the convex surface. For a smaller diameter test

section ($\frac{5}{16}$ in. diam. and $4\frac{3}{8}$ in. radius of curvature) the heat-transfer-coefficient ratio is nearly a constant. For the angular position between 25 and 50 degrees, the ratio is approximately 2. The concave and convex heat-transfer coefficients tend to minimize near the transposed critical temperature, opposed to the increased effect noted for the $\frac{1}{2}$ -inch-diameter test section.

3. The gaseous data may be adequately described by a coefficient K variation in the Dittius-Boelter type equation. The concave coefficient appears to approach a constant (fig. 3), while the convex coefficient appears to attain a minimum and then increase as the angular position increases (fig. 4). Temperature fluctuations begin at this minimum, perhaps indicating transition to an unstable condition (augmented turbulence).

4. The near-critical and two-phase data, while difficult to compare to a straight tube, were compared at the convex surface by using either a modified Dittius-Boelter type equation (similar to that of ref. 2) or by matching data at similar operating conditions (table I and fig. 5). The results indicate the convex coefficients to be lower but relatively close to the straight tube heat-transfer coefficient.

5. Visual observations of two-phase flow (nitrogen) within the "film boiling" region indicate little or no secondary flow (as is observed in single-phase flow), (fig. 6(a)); centrifuging effects apparently predominate (fig. 6(b)). Some near-ciritcal data suggest that both secondary flow and centrifuging effects are present. Thus, for analysis of the near-critical data in a curved tube, two important variables appear to be momentum of the fluid in the direction of flow and the density gradient from the wall to the bulk.

REFERENCES

1. Deissler, R. G.: Heat Transfer and Fluid Friction for Fully Developed Turbulent Flow of Air and Super Critical Water with Variable Fluid Properties, Trans. ASME 76, 73-85 (1954).

2. Hendricks, R. C., Graham, R. W., Hsu, Y. Y., and Medeiros, A. A.: Correlation of Hydrogen Heat Transfer in Boiling and Supercritical Pressure States, ARS Journal (1962).

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TABLE I. - COMPARISON OF CALCULATED TO MEASURED

HEAT-TRANSFER COEFFICIENT. CALCULATED

COEFFICIENT BASED ON

STRAIGHT TUBE DATA

[d = 5/16, R = $4\frac{3}{8}$ curved tube data;
EL = 16 in., θ = 27°.]

Run	H_{calc}	H_{exp}	Δ	$\frac{\Delta}{H_{calc}} \times 100$
1356	0.00353	0.00296	0.00295	16
1357	.01139	.00704	.00435	[a]40
1358	.0041	.00377	.00033	8
1359	.00482	.00446	.00036	3
1360	.00261	.00265	.00004	1
1361	.00619	.00574	.00045	7
1369	.00265	.00277	-.00012	-4
1370	.00543	.00491	.00052	9
1371	.00428	.00378	.0005	12
1372	.00323	.00296	.00027	8
1373	.00673	.00561	.00092	14
1362	.00322	.00351	.00029	9
1363	.00362	.00338	.00024	7
1364	.00234	.00265	.00021	9
1365	.00416	.00377	.00039	9
1366	.00269	.00284	-.00015	-6
1368	.00395	.00322	.00073	5
1377	.00707	.00585	.00122	17
1355	.00606	.00398	.00205	35

[a]Out of range of curve fit.

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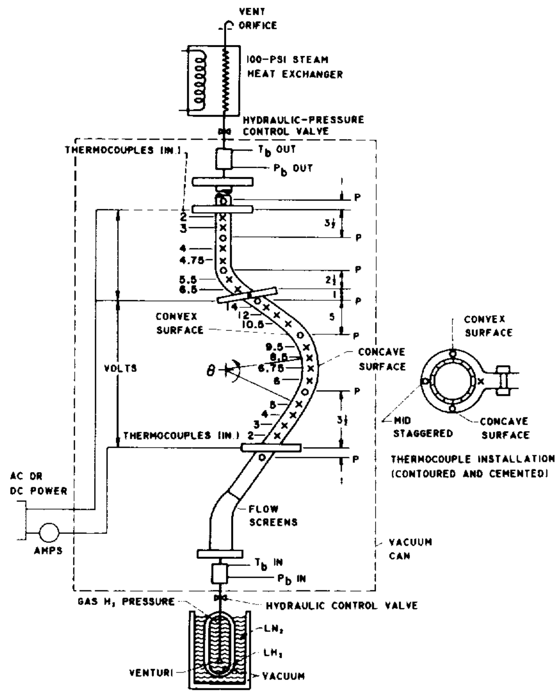

Fig. 1. - Schematic diagram of flow system and test section.

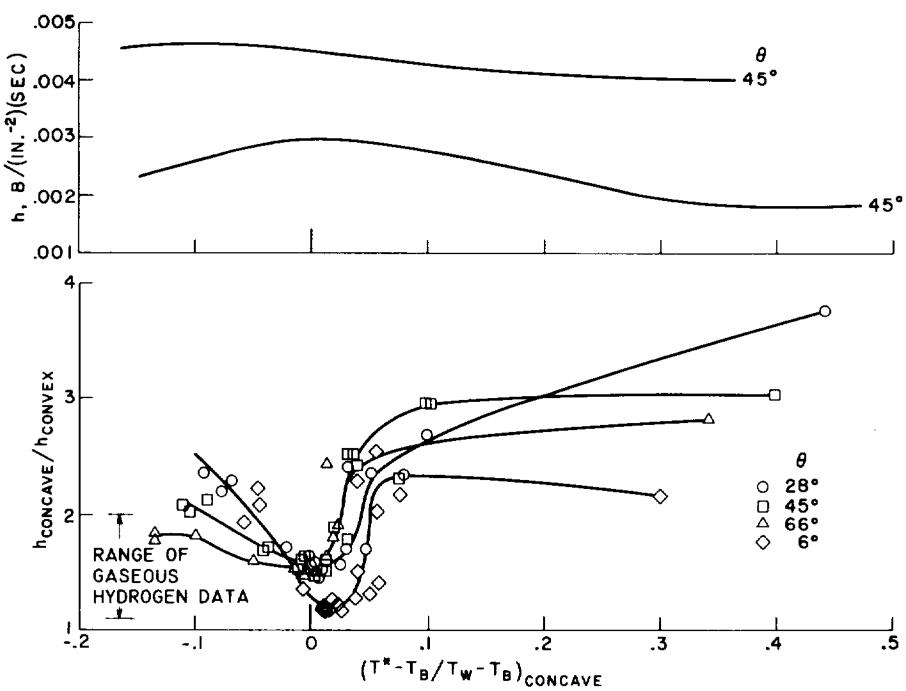

Fig. 2. - Heat transfer coefficient ratio for various angular positions and Eckert parameters (near-critical hydrogen; 1/2 inch diameter, [illegible] inch radius of curvature test section).

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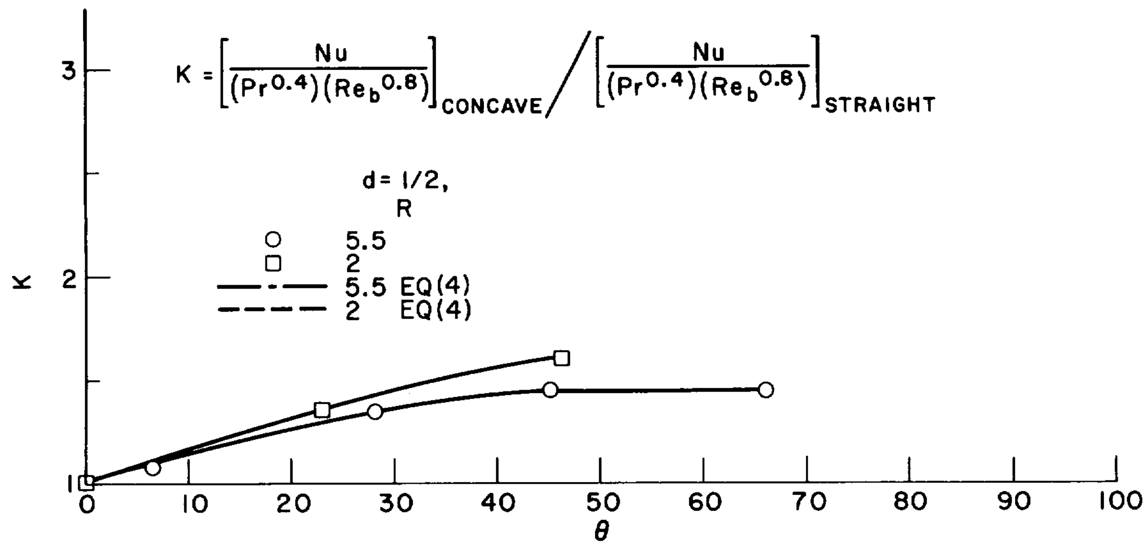

Fig. 3. - Variation of K with angular position (gaseous hydrogen).

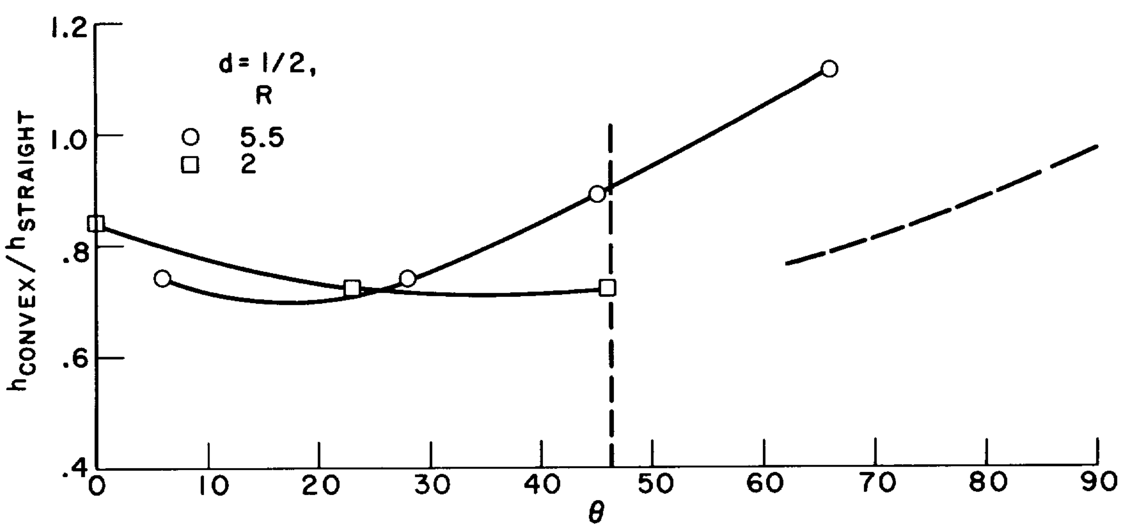

Fig. 4. - Variation of heat transfer ratio with angular position (gaseous hydrogen).

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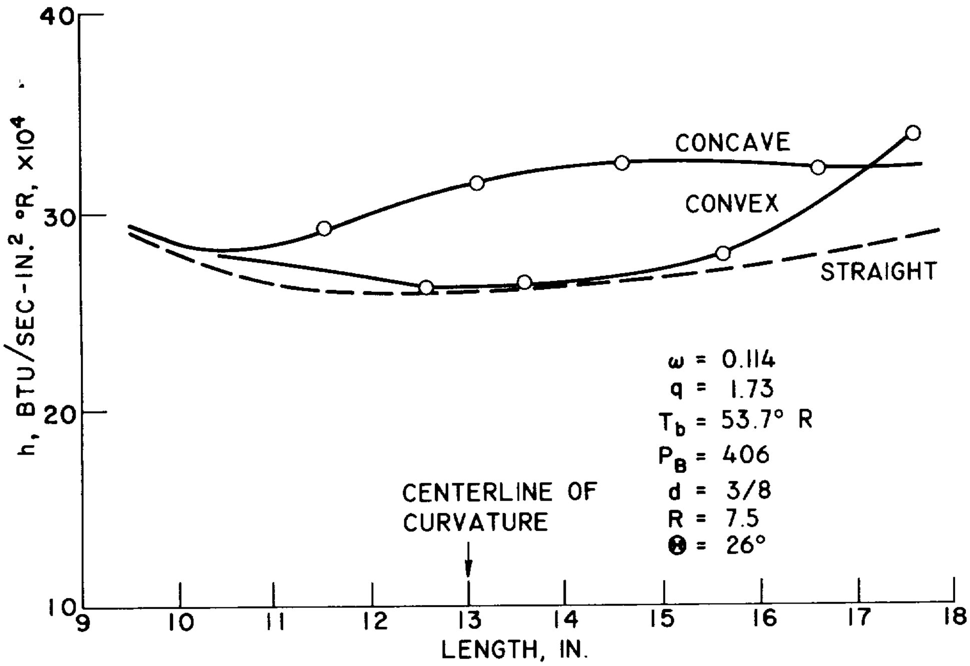

Fig. 5. - Comparison of convex to straight tube heat-transfer coefficients for a large radius of curvature (supercritical liquid hydrogen).

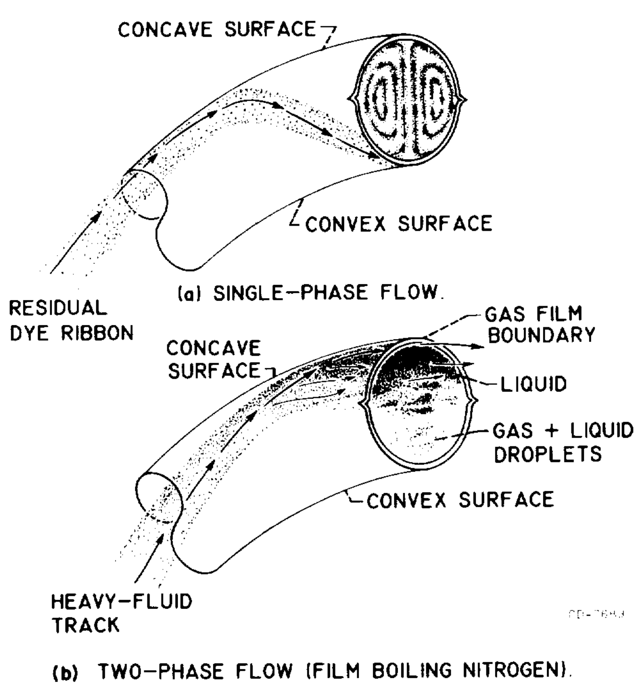

Fig. 6. - Observations of fluid flow in curved tube.